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Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective

Francesco Goia [a,b,c,*], Matthias Haase [b,c], Marco Perino [a]

[a] TEBE Research Group, Department of Energy, Politecnico di Torino, Torino, Italy
[b] The Research Centre on Zero Emission Buildings, Faculty of Architecture and Fine Art, Norwegian University of Science and Technology, Trondheim, Norway
[c] SINTEF Building and Infrastructure, Trondheim, Norway

HIGHLIGHTS

- ▶ Integrated thermal-daylighting simulations on a low energy building are performed.
- ▶ Optimal WWR of the façade that minimizes the total energy demand is searched.
- ▶ Optimal WWR are found in the range 35–45%, regardless the orientation, in a temperate oceanic climate.
- ▶ If state-of-the-art technologies are used, WWR does not play a crucial role (maximum influence: 11%).
- ▶ The optimal configurations are tested against different building geometries and HVAC efficiencies.

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ABSTRACT

The building enclosure plays a relevant role in the management of the energy flows in buildings and in the exploitation of solar energy at a building scale. An optimized configuration of the façade can contribute to reduce the total energy demand of the building.

Traditionally, the search for the optimal façade configuration is obtained by analyzing the heating demand and/or the cooling demand only, while the implication of the façade configuration on artificial lighting energy demand is often not addressed.

A comprehensive approach (i.e. including heating, cooling and artificial lighting energy demand) is instead necessary to reduce the total energy need of the building and the optimization of the façade configuration becomes no longer straightforward, because non-linear relationships are often disclosed.

The paper presents a methodology and the results of the search for the optimal transparent percentage in a façade module for low energy office buildings. The investigation is carried out in a temperate oceanic climate, on the four main orientations, on three versions of the office building and with different HVAC system's efficiency. The results show that, regardless of the orientations and of the façade area of the building, the optimal configuration is achieved when the transparent percentage is between 35% and 45% of the total façade module area. The highest difference between the optimal configuration and the worst one occurs in the north-exposed façade, while the south-exposed façade is the one that shows the smallest difference between the optimal and the worst configuration.

1. Introduction

It is a well-established belief that the façade can play a crucial role in the management of energy flows and thus contribute to achieve energy efficiency in building. The conventional approach focuses mainly on the "negative" aspects related to the role of the façade (i.e. on the heat loss during the heating season), and in this framework the transparent elements of the façade are the weakest spots. However, it is now becoming more and more common to consider the "positive" features of the transparent part of the façade, such as the ability to exploit the solar gain to reduce the heating demand (passive solar heating), and the possibility to provide daylighting for the indoor environment.

One of the main ways through which the façade configuration affects the total energy efficiency of the building is the balance between opaque and transparent elements. The relevance of this

* Corresponding author at: TEBE Research Group, Department of Energy, Politecnico di Torino, Italy. Tel.: +39 011 090 4519; fax: +39 011 090 4499, Faculty of Architecture and Fine Arts, Norwegian University of Science and Technology, Trondheim, Norway. Tel.: +4773550275; fax: +4773595094.
E-mail addresses: francesco.goia@polito.it, francesco.goia@ntnu.no (F. Goia).

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parameter on the behavior of the façade has been demonstrated in a recent sensitivity analysis on an office building equipped with automated shading [1]. The analysis of the balance between the transparent and the opaque part of a façade can thus provide useful information for the design of the future buildings that present low energy demand, as required by the recent EU directive (EPBD recast) [2].

The configuration of the façade can affect three terms of the annual energy demand of a building, as defined in EN 15603 [3]: the energy need for heating (E_H), the energy need for cooling and dehumidification (E_C), the energy need for lighting (E_L). The other three terms of the total energy demand of the building – i.e. energy need for ventilation and humidification, hot water and other services – are not directly affected by the configuration of the façade.

The aim of this paper is to demonstrate that the optimization[1] of a façade requires the contemporary evaluation of E_H, E_C, and E_L, and that integrated thermal-daylighting simulations are necessary. The paper investigates a hypothetical, single skin façade module, realized with market-available, state-of-the-art technologies. A methodology to assess the optimal configuration of the façade module (optimal Window-to-Wall Ratio[2], WWR) is then presented. The research activity is aimed at giving practical information to façade manufacturers and practitioners about the "average" configuration of a façade for an office building which incorporates best available technologies in the framework of low energy buildings.

Since climate plays a role in the configuration of the façade, a central Europe climate, representative of a wide area of Atlantic and Central Europe, was chosen.

Of course, the actual optimal configuration depends on the exact features of the building, but this study can provide a method, as well as a rule-of-thumb, that can be used during the preliminary design phase. Furthermore, it highlights some aspects that must be taken into account during the detailed design phase and points out the relevance of an integrated analysis.

2. State of the art

The impact of fenestrations on the energy performance of the building is a topic which has been investigated for a long time. Since the first analyses, dated in the 1970–1980 [4,5], the implication of the façade on the lighting energy demand was pointed out. It is important to mention that even though most of the analyses carried until now focused on either thermal or lighting aspect, a global energy approach was already adopted in some of the first investigations [6]. The most relevant finding of these research activities was the relevant role of the WWR: optimum WWR resulted in significant energy saving (more than 50%) for heating, cooling and lighting.

In the following years, the influence of the materials [7–9], the dimension of the fenestration [8,9] and the integration of active elements as PV panels [10] have been investigated. A particular focus has been placed on office buildings [11] and on the implications of the façade configuration in different climates [12], including heating-dominated [10] and cooling-dominated [13] climates. Results are difficult to be summarized because of their extent, but it is possible to notice a general trend towards a lower influence of the WWR on the building energy performance as it improves – i.e. when more efficient technologies (e.g. more insulated buildings, more efficient HVAC systems, more efficient lighting) are employed.

With the increase of research activities on low energy buildings, the impact of the fenestration on this kind of construction has been evaluated too [14–16], both for heating-dominated climates [14] and for cooling-dominated climates [16]. However, the focus was often placed only on thermal aspects, neglecting the implications on the visual environment and on lighting energy demand. In particular, artificial light energy consumption was not evaluated in the majority of the last cases, making it difficult to obtain results in a total energy perspective. In addition, research activities focusing only on potential savings due to a better use of daylighting can be also found [17].

Recently, the trade-off between energy and visual comfort has been investigated for glazing systems without solar shading devices [18]. It was pointed out that windows optimized exclusively for visual comfort leads to large energy consumption. On the other side, the optimization of the window size based on low energy consumption only does not meet visual acceptance criteria. A tradeoff is thus necessary.

The relevance of the incorporation of shading systems for both solar and visual control in office buildings is highlighted by a research on fixed or dynamic solar shading systems [19]. In particular, the influence of both the size of the window and the shading device's typology was investigated. The façades with dynamic solar shading showed the best performance with respect to total energy demand, and façades with fixed solar shading the worst. Furthermore, it was found that, in a Danish climate, the difference in total energy demand between the worst and best-performing façade, for a given orientation, does not exceed 16%.

The integration of shading devices into fenestrations increases the degree of complexity of the system. In fact, the use of shading devices provides considerable advantages [19–23] compared to a static fenestration, but different typologies and control strategies can be adopted – and different performance achieved. On this topic, integrated thermal and daylighting analyses for perimeter office spaces in Montreal were carried out [20], evaluating the impact of WWR on visual and thermal performance and artificial lighting. The results showed that, for south-facing facades, a WWR = 30% can ensure natural daylight illuminance values higher than 500 lux for 76% of the working time in a year. Larger windows do not result in significant increase in useful daylight. Compared with the reference case without shading, an appropriate shading control (exterior roller shade) can halve the cooling energy demand. Although the artificial lighting demand is increased in case of solar shading, an optimal solution can be found and a reduction of 12% in the total energy demand achieved.

The impact of interior roller shades in combination with different window sizes was analyzed in two different climates (Chicago and Los Angeles), in small private offices [22]. The complex interactions of the several parameters were analyzed and discussed in details, demonstrating that automated shades may lead to reduction (or increase) of the total energy demand, depending on the combination of the other parameters. Among the results should be highlighted that façades with a transparent percentage in the range 30–50% can determine the lowest total energy demand in particular cases.

The adoption of overhanging and/or blinds and of different WWR in an office building located in Santiago de Chile was recently investigated by means of integrated thermal lighting simulations [23]. It was shown that WWR influences to a great extent the energy demand, especially when no sun shading systems/overhanging are exploited. A fully glazed façade may determine an energy demand for cooling and heating more than six time higher

[1] In this paper, the term "*optimal configuration*" means the Window-to-Wall Ratio (WWR) that minimizes the annual primary energy demand of the building. In other words, the optimization concerns exclusively the WWR, while all the other variables (e.g. the materials of the façade modules, the properties and the performance of the subcomponents) are kept constant. The term "*annual primary energy demand*" means the sum of the energy demand for heating, cooling and lighting.

[2] The Window-to-Wall Ratio (WWR) is defined as the ratio between the net glazing area and the gross exterior wall area.

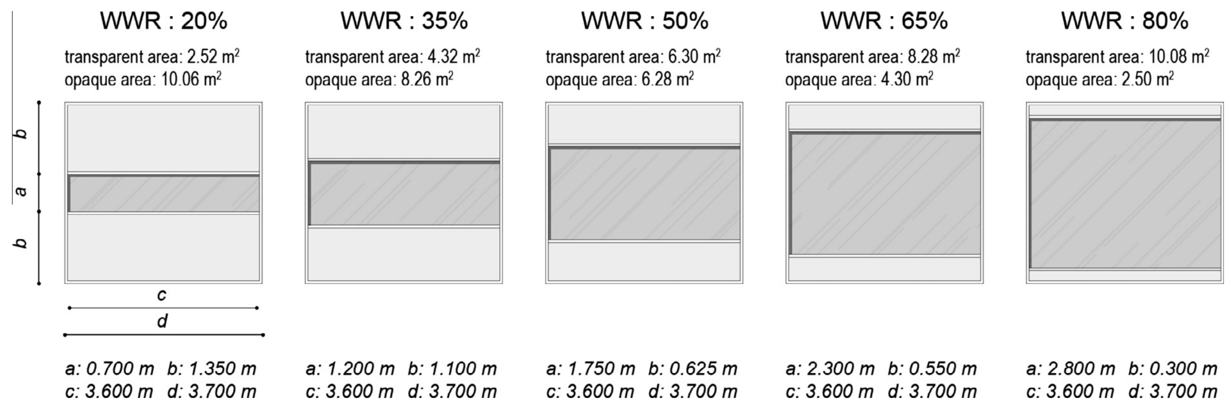

Fig. 1. Geometry of the simulated façade modules characterized by different WWR.

than that of a façade with WWR = 20%, external solar protection and selective glazing. This latter configuration is capable of providing useful daylight during around 80% of the working time.

Another additional complexity that arises with integrated solar shading system is the choice of the control criteria [24]. Usually, the shading device is controlled as a function of the glare risk, or as a function of the incident (or transmitted) solar irradiance, or activated in case of cooling load, or its displacement is based on the prediction of the indoor illuminance level. The selection of an appropriate control strategy plays a crucial role in the interior conditions and in the energy saving potentials. For office rooms, it is preferable not to let direct sunlight enter, and in the case of the adoption of venetian blinds, they should be rotated to block sunrays.

As far as the numerical tools are concerned, the literature review reveals that, when such dynamic shading systems are modeled, it is difficult to perform integrated thermal-lighting simulations with a high degree of accuracy, especially for non-expert users and practitioners. Most of the research activities reported in literature were carried out with specifically developed codes. Numerical tools that accurately simulate either thermal or lighting aspects are well-available, but integrated software tools very often make use of simplified methods and assumptions that may reduce the degree of accuracy.

3. Methods

The implications of the façade configuration on the energy consumption of an office building are investigated by means of a façade made of prefabricated modules. The choice of modeling a façade in terms of façade modules is due to the fact that a façade module is a particularly relevant case study as far as the WWR is concerned. Furthermore, façade modules are gaining popularity, especially in present-day commercial and office buildings, and are seen as potential, market-available technology, to increase energy efficiency in buildings – both in new constructions and in renovations.

3.1. Façade module technology

The façade module is a single skin façade technology, 3.7 m width and 3.4 m height, and it is realized with market-available technologies. The façade module is composed of two surfaces: a transparent part and an opaque part. The transparent surface is made of a triple glazing with low-E coatings (clear glass panes) and integrated external solar shading devices – i.e. a highly-reflective external venetian blind system (blind slate reflectivity: 80%). When displaced, the venetian blinds cover the entire net glazing area; the angle of the venetian blinds is adjusted continuously in order to block the direct solar rays. The *U*-value of the glazing is 0.7 W m^{-2} K^{-1}, the SHGC is 0.46, and the visible transmittance is 0.53.

The opaque part is realized with a sandwich panel, made with 0.025 m thick Vacuum Insulation Panels, a 0.12 m thick rockwool insulation layer and some plasterboard layers (total thickness of the plasterboard layers is 5 cm). The outer surface of the opaque surface is made of a metal panel. The *U*-value of the opaque sandwich is 0.15 W m^{-2} K^{-1}. The façade module presents also a thermal break aluminum frame with *U*-value of 1 W m^{-2} K^{-1}.

Five different WWR are used during the search for the optimal configuration: from WWR = 20% (equivalent to ca. 2.5 m^2 transparent area each module) to up to WWR = 80% (equivalent to ca. 10.0 m^2 transparent area). The surface of the façade module that is not transparent is made of both the aluminum frame (around 10% of the total façade module area) and the opaque sandwich panel. Thermal bridges due to module-to-module connections are neglected. Details on the different geometries and aspects of the façade module are illustrated in Fig. 1.

3.2. Office building specifications and data processing

The optimal configuration of the façade module is investigated for an office building characterized by a typical layout, located in Frankfurt (Germany), which belongs to a temperate-oceanic climate – Cfb according to Köppen climate classification [25].

The plan concept of the building is derived from a "typical" office building developed in the frame of the IEA Annex 27 activity [26]. It presents a central corridor with cell offices on both the sides of the corridor; building services, staircase and lifts are at the two ends of the corridors (Fig. 2a). The cell office dimensions are: 3.6 m (w) × 5.4 m (l) × 2.7 m (h); the interior surface visible reflectance coefficients of the walls, ceiling and floor are 70%, 70% and 40% respectively. Each cell office has one façade that borders with the outdoor environment, and it is made of a façade module. The office building has a concrete structure with concrete slabs and lightweight interior partitions, an atrium area at ground level (heated) and an underground level (not heated). Specifications of the building services and settings are given in Table 1; the internal loads and lighting-related data are illustrated in Table 2 and derived from [27]; mechanical ventilation specifications are taken from [28]. The occupation time is set 8 am–5 pm, Monday through Friday.

After the simulations are performed, the building is virtually "divided", along the axis of the central corridor, in two volumes (half of the total volume each), and each of the two volumes is associated with a façade orientation (cf. Fig 2b and c). Since the building is considerably smaller in width than in length, the building presents two

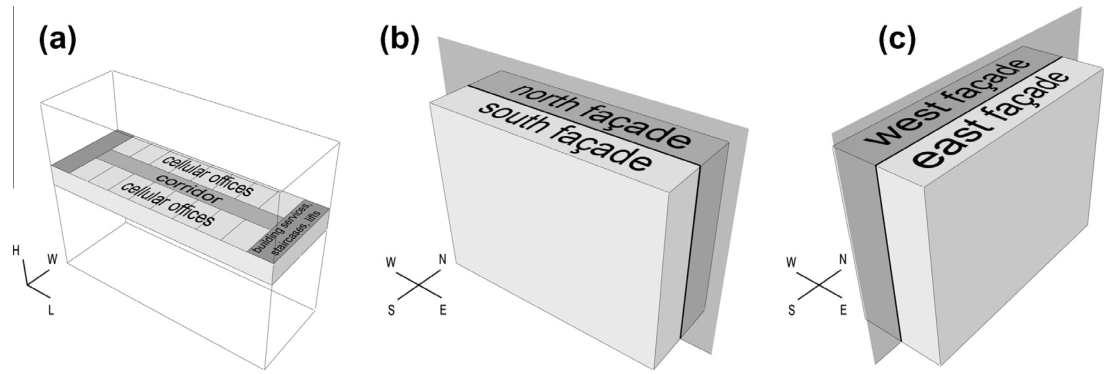

Fig. 2. (a) Plane concept of the office building. (b) Subdivision of the building volume in two volumes associated to two main orientations.

Table 1
HVAC system specifications.

	Temperature set-point (heating/cooling)		HVAC specification				
	Summer (°C)	Winter (°C)	Mechanical ventilation ($l\,s^{-1}\,m^{-2}$)	Heat recovery efficiency (–)	Specific fan power ($kJ\,m^{-3}$)	$SCOP_{heating}$ (–)	$SCOP_{cooling}$ (–)
Occupancy Mon–Fri 8 am–5 pm	20/24	23/26	1.42	0.80	1.5	2.6	3.8
Non occupancy	17/27	20/29	0.70	0.80	1.5	2.6	3.8

Table 2
Internal loads and artificial light (office rooms only).

	Internal loads		Lighting	
	People ($W\,m^{-2}$)	Equipment ($W\,m^{-2}$)	Installed power ($W\,m^{-2}$)	Illuminance set-point (lux)
Occupancy Mon–Fri 8 am–5 pm	11.5	10.0	7.5	500
Non occupancy	0.0	1.0	7.5	0

main façades – i.e. north façade and south façade, if the main corridor is aligned along the axis east–west, or east façade and west façade if the corridor is aligned along the axis north–south. Therefore, during the data post-process phase, each building only presents two façades: south and north façades (cf. Fig 2b), or east and west façades (cf. Fig. 2c). As a consequence, the energy demand associated with a single orientation takes also into account the energy demand associated to surfaces and volumes that do not necessarily present this orientation.[3] The reason for modeling an entire building instead of a single cell office, as some other research activities do (e.g. [17–20]), is to correctly take into account the energy demand of the entire building – which is not made only by cell offices. This way, the energy performance obtained for a façade orientation is more representative than a simulation concerning the cell office alone, because closer to the real situation.

3.3. Optimization procedure and simulations

The aim of the search is to find the WWR of the façade module that minimizes the total energy demand of the building E_{tot} (Eq. (1)), where E_H is the heating primary energy demand, E_C is the cooling primary energy demand, and E_L is the lighting primary energy demand, on a yearly base. The conversion factor for electrical energy (kW h_{ee}) to primary energy (kW h_{pe}) is 2.5 (kW h_{pe}/kW h_{ee}).

$$E_{tot} = E_H + E_C + E_L[\text{kW h}_{pe}\ \text{m}^{-2}] \quad (1)$$

If the search for the optimal WWR is considered as a problem of allocation of resources (the optimal allocation of glazing surface and opaque surface in a given façade module surface), the objective function is (Eq. (2)):

$$f : \min\{E_{tot}(\text{WWR})\} \quad (2)$$

Since the transparent part incorporates a solar shading system and this introduces more dynamics to the façade module, a preliminary analysis on the influence of this system on the final result is needed. In particular, it is necessary to identify the best strategy for the activation of the solar shading device since it has huge implications on the final outcomes. After some preliminary investigations, that are not reported here for the sake of brevity, the following strategy is adopted: the solar shading devices are activated if the zone cooling rate in the previous time-step is non-zero and if the solar radiation incident on the window exceeds a certain set-point value. The adopted strategy is a compromise between a strategy that focuses only on thermal aspects and a strategy that is based on daylight exploitation. In fact, the choice to displace the venetian blinds in case of a simultaneous cooling load and solar irradiance exceeding a target value avoids the activation of the shading systems in case of cooling loads caused by internal gains. This strategy should therefore provide adequate daylight still avoiding the excess of cooling load.

However, the determination of the optimal set-point value for the activation of the solar shading (i.e. the set-point value that determines the lowest total energy demand) is not straightforward: too low set-point values may reduce cooling energy demand, but increase lighting energy demand and heating energy demand; too high set-point values can produce the opposite effect. Thus, the

[3] E.g. In a building where the corridor is aligned along the axis east-west, the south orientation also takes into account volumes that have a west and east orientations (where the building services, lifts and staircases are). The north orientation follows the same rule.

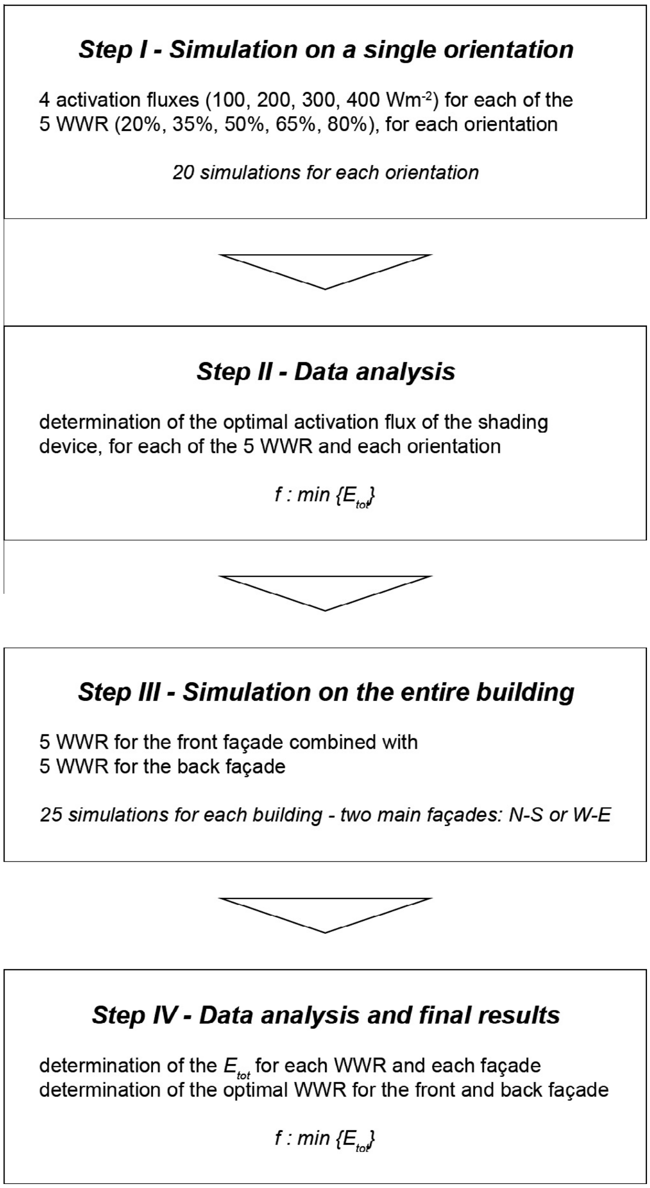

Fig. 3. Schematic illustration of the workflow and different simulations performed to determine the optimal WWR for each orientation.

search for the best set-point value becomes an optimization procedure itself. This procedure must be repeated for each orientation and for each WWR, since different orientations and WWR may have different optimal set-point values.

In order to perform this task, it is thus necessary to analyze one by one the orientations, and to test different WWR for the same orientation. Therefore, during this first round, the façade module (with a certain WWR) is adopted only on the orientation under investigation, while the opposite orientation is made of a fully opaque wall. For each WWR (20%, 35%, 50%, 65% and 80%), different set-point values for the activation of the solar shading system are tested: 100 W m^{-2}, 200 W m^{-2}, 300 W m^{-2}, and 400 W m^{-2}. In total, 20 combinations are therefore evaluated.

Once the optimal activation set-point for each WWR and orientation is found, a second round of simulations is then performed: 25 possible combinations are investigated for each building and couple of orientations, by combining five different WWR on two opposite façades. During this round, different WWRs adopt the optimized solar shading activation set-points previously determined. A scheme of the workflow is illustrated in Fig. 3.

3.4. Integrated thermal-lighting simulations and limitations

The integrated thermal and daylight simulations are carried out using the *EnergyPlus* software [29], performing calculations on hourly basis for the entire year. A daylighting calculation is performed at each heat-balance time-step when the sun is up. The electric lighting control system (continuous dimming control) is simulated to determine the lighting energy needed to make up the difference between the daylighting illuminance level and the design illuminance set-point. Finally, the zone lighting electric reduction factor is passed to the thermal calculation, which uses this factor to reduce the heat gain from lights [30]. One reference point for the daylight calculation is chosen in each cell office, placed on the centre line of the office, at 3.6 m from the façade, at a height of 0.80 m above the floor.

Ramos and Ghisi [31] analyzed the reliability of the *EnergyPlus* software in daylight simulation, for different room geometries, WWR and locations. It was pointed out that *EnergyPlus* presents some problems in the calculation of both Daylight Factors and external illuminance values, when compared to a more advanced software tool for daylight simulations – i.e. *Radiance*. In particular, *EnergyPlus* presents some inaccuracies in the calculation of internal reflections – the greater the importance of the portion of light reflected in the indoor environment, the greater the difference between *EnergyPlus* and *Radiance*. Furthermore, the comparison between calculated and measured external horizontal illuminances shows great differences both for diffuse and direct illuminances – *EnergyPlus* overestimates these values.

However, it must be stated that a great similarity was found between the internal illuminace obtained by *EnergyPlus* and by *Radiance* – maximum difference of 20%. This means that, even if EnergyPlus shows some limitations in daylight calculation, it is still possible to perform integrated simulations with this code, and to evaluate the impact of the configuration of the façade on the energy demand for lighting.

3.5. Daylight analysis

Daylighting analyses are carried out by making use of two performance indexes: the Daylight Autonomy (*DA*) [32] and the Useful Daylight Illuminance (*UDI*) [33]. The DA measures the percentage of the working year during which the illuminance threshold on the working plane (i.e. 500 lux) is maintained by natural light alone. The *UDI* measures how often the daylight on the working plane is within a specific illuminance range. Therefore, three different *UDI* are used, following the range limits proposed by Nabil and Mardaljevic [33]:

- $UDI_{100\text{–}500}$, which shows the percentage of the working year when the daylight illuminances, although not enough to meet the threshold, are considered effective either as the only source of light or combined with artificial lighting;
- $UDI_{500\text{–}2000}$, which shows the percentage of the working year when the daylight illuminances are perceived either as desirable, or at least tolerable, and no artificial lighting is used;
- $UDI_{>2000}$, which shows the percentage of the working year when the daylight illuminances may produce visual or thermal discomfort, and can therefore give an indirect, quantitative yet simplified information about the glare discomfort risk.

Although limits or suggested values for *UDI* have not yet been standardized and fully accepted, it is straightforward that high $UDI_{500\text{–}2000}$ values (e.g. >50%) result in suitable (or at least acceptable) exploitation of daylighting; even higher values are sign of a proficient design of natural light exploitation. A less direct relationship can be instead drawn as far as $UDI_{>2000}$ is concerned, which is correlated to glare discomfort risk. If it is probably true that low values of $UDI_{>2000}$ may result in less glare discomfort risk, it is not clear what can be a (upper) limit value for this metric. Considering that very low values of $UDI_{>2000}$ cannot be reached even in well-designed indoor environments, a reasonable threshold value that may work as a rule-of-thumb can be found in the range of 10–20% (the lowest, the best).

3.6. Reliability analyses

In order to assess the reliability of the achieved results (i.e. the optimal WWR), two further investigations are performed: the sensitivity of the results is tested, within the same building typology, against different building geometries; moreover, the sensitivity is also tested against different HVAC systems that present higher or lower efficiencies.

In order to test the sensitivity with respect to the building geometry, three configurations (different geometries, same layout) of the same office building are simulated. The three building (codes: B1, B2 and B3) share the same plan concept, technologies and services and the details of their geometry are given in Table 3. A change in the depth of the building was not considered since this would probably result in a different plan concept (e.g. a double corridor configuration) and thus in a different building typology. The Surface-Area-over-Volume ratio, SA:V, for each building is also given as a synthetic parameter of the building geometry: it is defined as the ratio between the total surface area of the building that surrounds the heated/cooled volume and is exposed to outdoor conditions (including the surface area in contact with the ground), and the heated/cooled volume of the building.

The sensitivity of the optimal façade configuration with respect to different efficiencies of the HVAC system is investigated too. The efficiency of the SCOP (Seasonal Coefficient of Performance) is increased by 25% or decreased by 25%. In Table 4, the HVAC efficiencies are reported. Four possible configurations are evaluated and resumed in Tables 5:

(1) a reference $SCOP_{heating}$ and an more efficient $SCOP_{cooling}$;
(2) a reference $SCOP_{heating}$ and a less efficient $SCOP_{cooling}$;
(3) a more efficient $SCOP_{heating}$ and a reference $SCOP_{cooling}$;
(4) a less efficient $SCOP_{heating}$ and a reference $SCOP_{cooling}$.

The reference building (B2, SA:V = 0.25 m^{-1}) is used during this phase, and the combination of different efficiencies and different building geometries is not investigated.

Table 3
Dimensions of the three office buildings B1, B2 and B3.

Code	SA:V (m^{-1})	Length (L) (m)	Width (W) (m)	Height (H) (m)
B1	0.20	53.3	14.4	90.1
B2	0.25	45.9	14.4	28.9
B3	0.30	38.5	14.4	18.7

Table 4
SCOP of the reference HVAC and of the more/less efficient systems.

		Reference HVAC	More efficient HVAC (efficiency: +25%)	Less efficient (efficiency: −25%)
$SCOP_{heating}$	(–)	*2.60*	3.25	1.95
$SCOP_{cooling}$	(–)	*3.80*	4.75	2.85

Table 5
Details of the combinations of $SCOP_{heating}$ and $SCOP_{cooling}$ for the four tested configurations.

		HVAC (1)	HVAC (2)	HVAC (3)	HVAC (4)
$SCOP_{heating}$	(–)	2.60	2.60	3.25	1.95
$SCOP_{cooling}$	(–)	4.75	2.85	3.80	3.80

4. Results

4.1. Optimal set-point value for activation of solar shading device

In Table 6, the optimal set-point values for the activation of the solar shading systems, for each orientation and WWR, are presented. In Figs. 4 and 5, the extra energy demand values caused by non optimal set-point values are plotted – when the extra energy demand is 0, the optimal set-point value is reached.

The optimal activation set-point decreases as the transparent percentage increases. This can be seen in Fig. 4a for a south orientated façade. The activation set-point value that minimizes the total energy demand is 400 W m^{-2} for a WWR = 20%, while the best set-point value is 100 W m^{-2} for WWR = 80%. Intermediate WWR require intermediate activation fluxes. The highest deviation between the optimal set-point value and the worse set-point value is achieved when WWR = 80% and a set-point of 400 W m^{-2} – 6% more energy than in the case of optimal activation set-point.

Solar shading devices should not be placed on a north-exposed façade (cf. Fig. 4b), since the lowest total energy demand is always achieved with activation flux equal or greater than 400 W m^{-2} – which never occurs on a north-exposed façade. A low set-point value (e.g. 100 W m^{-2}) reduces the ability to exploit daylight and increases the total energy demand of about 5–7%.

In the case of a west-exposed façade (Fig. 5a), the optimal set-point value is usually in the range of 200–300 W m^{-2}. The only façade module configuration that requires a different set-point value (400 W m^{-2}) is WWR = 20%, and a “wrong” set-point value may cause an increase in the total energy demand of about 3–4%. An east-exposed façade (Fig. 5b) shows a similar behavior to a west-exposed façade. The lowest set-point value (100 W m^{-2}) is always the least efficient, regardless the WWR. A non-optimal set-point value can increase E_{tot} about 4–6%.

4.2. Optimal configuration of the façade module

After the optimal activation set-point values are determined, two B2 buildings (having SA:V = 0.25 m^{-1}) are simulated: one with south and north façades (cf. Fig 2b); one with west and east façades (cf. Fig. 2c). Therefore, two façades are analyzed by means of the same set of simulations. 25 simulations for each building are then necessary, given by the combination of 5 different WWR for the front façade, and the same 5 different WWR for the back façade. This also determines that, for each WWR analyzed on the front façade, five different E_{tot} are obtained, depending on the configuration of the back façade. For each orientation analyzed, five E_{tot}

Table 6
Optimal set-point values for the activation of solar shading systems.

		Façade orientation			
		South (Wm^{-2})	North (Wm^{-2})	West (Wm^{-2})	East (Wm^{-2})
WWR façade module	20%	400	(400)	400	400
	35%	200	(400)	300	300
	50%	200	(400)	200	200
	65%	100	(400)	200	200
	80%	100	(400)	200	200

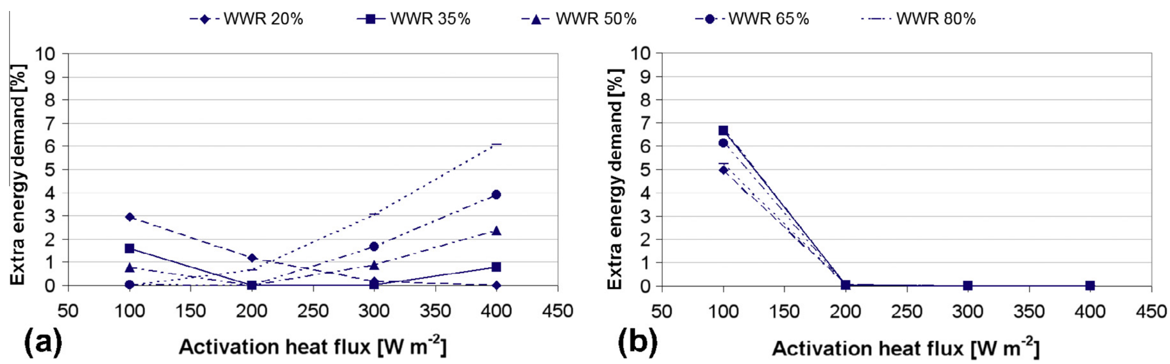

Fig. 4. Extra energy demand determined by non-optimal set-point values for the activation of solar shading devices, for different WWR: (a) south-oriented façade and (b) north-oriented façade.

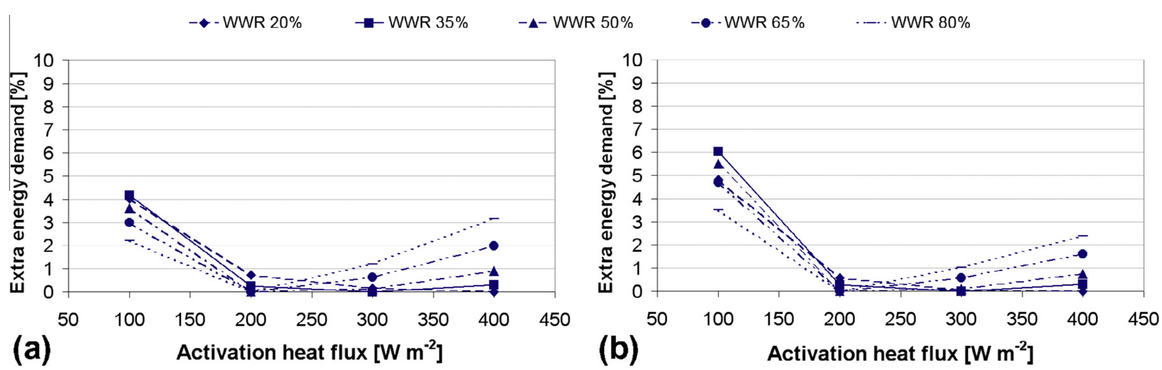

Fig. 5. Extra energy demand determined by non-optimal set-point values for the activation of solar shading devices, for different WWR: (a) west-oriented façade and (b) east-oriented façade.

parametric curves are thus obtained, where the parameter is the WWR of the opposite façade (Figs. 6 and 7).

It must be stated that, regardless the WWR of the opposite façade, the difference in E_{tot} for each WWR is always lower than 3% (south-exposed façade); furthermore, the parametric curves show the same pattern; moreover, the minimum value of E_{tot} is always reached around the same WWR. It is thus possible to affirm that the influence of the opposite façade is not significant for the scope of the research, even if it has an influence on the final E_{tot}.

In the case of a south-exposed façade module (Fig. 6a), the optimal configuration has a WWR between 35% and 45%. The difference in performance between the optimal and worst configurations is about 6%. The performance of a north-exposed façade (Fig. 6b) is also affected by the configuration of the opposite façade. In particular, when the WWR of the south-exposed façade is 20%, the performance of the north façade worsens considerably. A less relevant change in the performance of the façade is registered when the south façade has WWR > 35%. The optimal configuration of the north-exposed façade module, regardless the WWR of the opposite (south) façade, is achieved when WWR is in the range of 35–50%. The difference in the performance between the optimal and the worst WWR is just more than 11% – being WWR = 20% the worst configuration.

The performance of a west-exposed façade module (Fig. 7a) shows a lower dependence on the configuration of the opposite (east) façade. The dependence increases when the opposite façade has WWR > 50%. The difference between the optimal and the worst configuration is about 7%. The optimal configuration is achieved when WWR is in the range of 35–50%. The pattern of a east-exposed façade module (Fig. 7b) is similar to that of a west-exposed façade, and the best configuration is achieved when WWR is in the range of 35–45%. The difference in E_{tot} between the best and the worst configuration is about 8–9%.

4.3. Daylighting and visual environment

In Fig. 8 the DA, and $UDI_{100\text{-}500}$, $UDI_{500\text{-}2000}$ and $UDI_{>2000}$ are shown, for all the four main orientations, as functions of WWR. The values given in Fig. 8 are the average values over the entire work plane (0.80 m above the floor) of the office room, and include dynamic use of solar shading devices.

Regardless of the orientation, DA > 50% is obtained for façade configurations with WWR > 30%, and the maximum value of DA (about 70%) occurs when WWR = 80% (Fig. 8a). The similarities in the reached values, that seem to be independent from the façade orientation, can be explained considering that the activation of the venetian blinds differs for each WWR and orientation.

Even if a systematic investigation of the impact of façade configuration on glare is out of the scope of this work, the analysis of $UDI_{>2000}$ may give advice of the risk of glare discomfort in the room. In Fig. 8b it is possible to observe that the worst condition ($UDI_{>2000} \approx 25\%$) is reached in case of a south oriented façade, with WWR = 65%, or in case of an east oriented façade, with WWR = 80%. In the range where the optimal façade configurations lie (i.e. 35% < WWR < 50%), the $UDI_{>2000}$ is about 20% for a south exposed façade, and about 12% in east/west exposed façades.

In Figs. 8c and d $UDI_{100–500}$ and $UDI_{500–2000}$ are shown, respectively. In particular, it can be noticed that for about 45–55% of the time, the average illuminance values fall in the range of

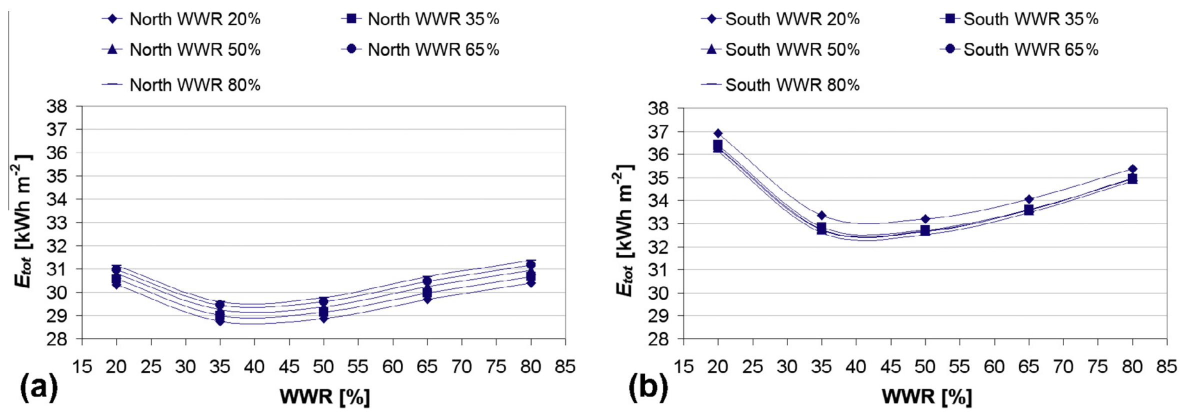

Fig. 6. (a) Total energy demand E_{tot} for a south-oriented façade module. (b) Total energy demand E_{tot} for a north-oriented façade module. B2, SA:V = 0.25 m^{-1}.

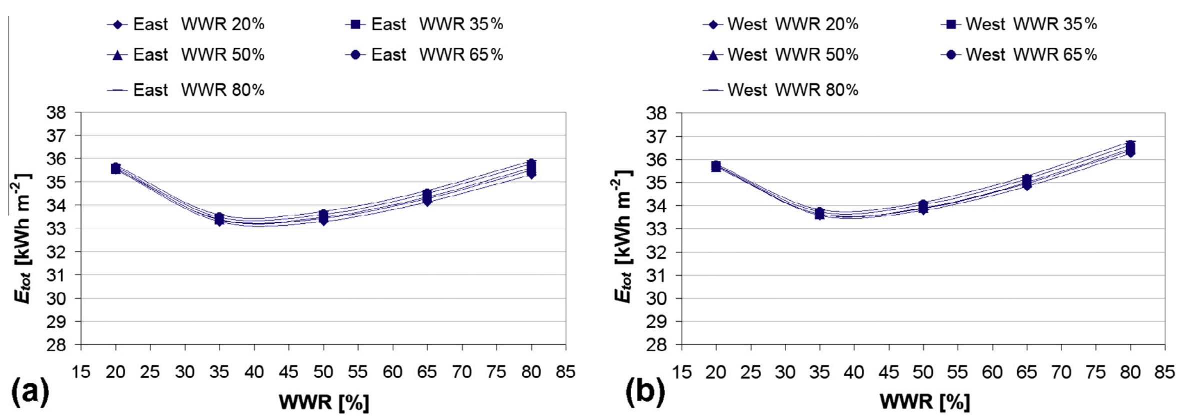

Fig. 7. (a) Total energy demand E_{tot} for a west-oriented façade module. (b) Total energy demand E_{tot} for an east-oriented façade module. B2, SA:V = 0.25 m^{-1}.

500–2000 lux, regardless of the façade orientation, provided that WWR > 30%. Within the optimal façade configuration range, south, west and east-exposed façades present $UDI_{500-2000} \approx 50\%$, and for a north-exposed façade $UDI_{500-2000}$ is in the range of 55–60%.

A more detailed analysis of the visual environment inside a south-exposed office is carried out too. The useful daylight illuminance distribution on the work plane is plotted in Fig. 9 as a function of the distance from the façade. Risk of glare discomfort is relatively high, regardless of the WWR, in the area closest to the façade, while far away from the façade $UDI_{>2000}$ < 30% (Fig. 9b). A good light distribution and uniformity is revealed by the analysis of $UDI_{500-2000}$ (Fig. 9a). For WWR > 35%, the central area of the office room (0.9–4.5 m from the façade) shows $UDI_{500-2000}$ in the range of 40–50%, meaning that for about half of the time the most important part of the office room presents satisfactory (and tolerable) daylight conditions, without the need of artificial light.

4.4. Reliability of the optimal configurations

4.4.1. Reliability with respect to the geometry of the building

During this phase, the average value of E_{tot} is used for each WWR of the façade module. As previously described, for each WWR analyzed on the front façade, five different E_{tot} are obtained, depending on the configuration of the back façade. The E_{tot} plotted in Figs. 10 and 11 are the average of the five different E_{tot}, obtained from the simulations with different WWR in the back façade. This can be done, as previously explained, because the influence of the opposite façade is found not to be relevant when the optimal configuration is investigated.

The analysis points out that the building geometry affects the total energy demand E_{tot} of the building – the lower the SA:V, the lower E_{tot}. However, it also shows that the optimal WWR is independent from the building geometry (Figs. 10 and 11): the patterns for the three buildings B1, B2 and B3 are very similar and the minimum value is always reached in the same interval.

Another analysis focuses on the influence on the energy demand for heating E_H. E_H as a function of the WWR is presented in Fig. 12a and b, for a south-oriented and a north oriented façade module, respectively. It is possible to notice that the three patterns are similar as far as the shape is concerned, but different in magnitude. It is also possible to notice that E_H is not really affected by WWR in a south oriented façade (Fig 12a). This is probably due to the relatively high internal loads, which contributes to reduce the energy demand for heating. Passive use of solar energy (solar heating), which may occur in case of large transparent surfaces, seems to have little or no influence on the heating energy demand. In fact, even if the activation of the shading also blocks possible passive solar gains, their influence on the final total energy demand is not significant: if solar shading systems were not activated, a reduction of maximum 7% of E_H would be achieved. On the other hand, the total energy demand of the building would increase considerably (up to 40% more) because of the increased cooling energy demand, E_C. In the case of a north-oriented façade module (Fig. 12b) a higher WWR in the façade module determines a higher energy demand for heating E_H which is contrast to what was observed in the south-exposed façade.

The energy demand for cooling E_C and lighting E_L (Fig. 12c and d, respectively) is almost independent from the building geometry. In

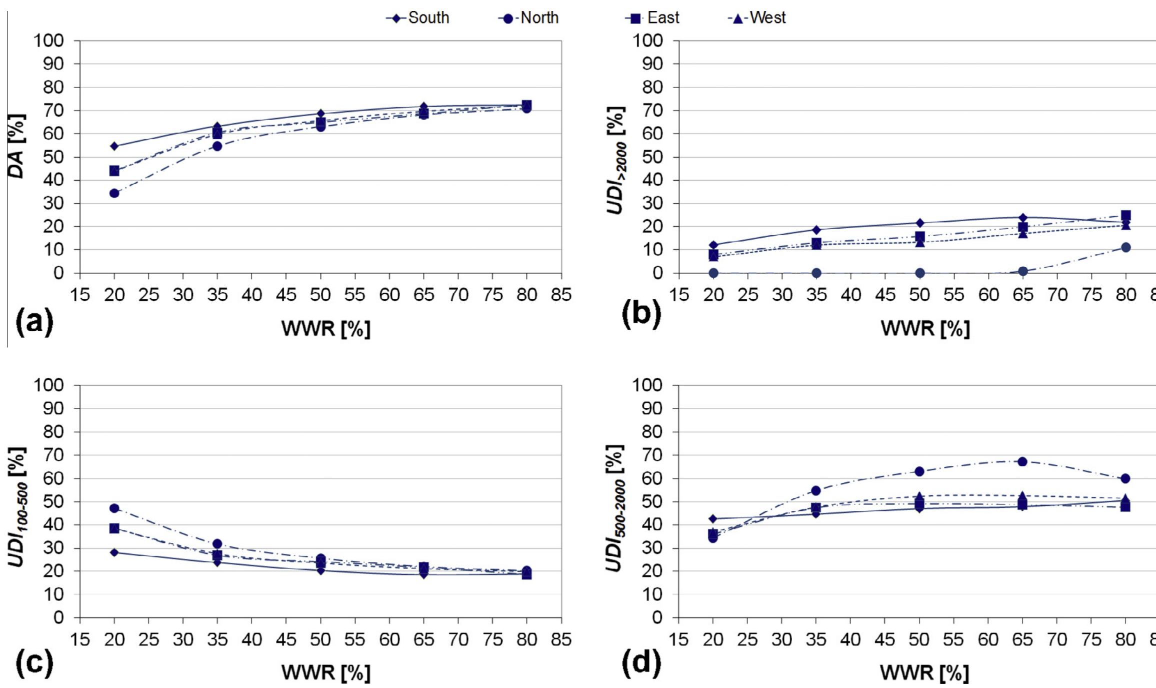

Fig. 8. (a) Daylight Autonomy for different orientations; b) $UDI_{>2000}$ for different orientations; (c) $UDI_{100-500}$ for different orientations; $UDI_{500-2000}$ for different orientations, B2, SA:V = 0.25 m^{-1}.

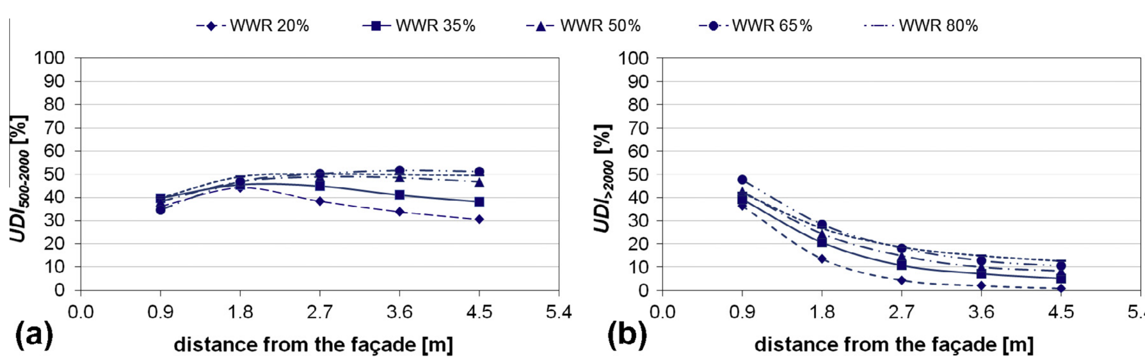

Fig. 9. (a) $UDI_{500-2000}$ for different WWR as a function of the distance from the façade (south-oriented façade module) and (b) $UDI_{>2000}$ for different WWR as a function of the distance from the façade (south-oriented façade module). B2, SA:V = 0.25 m^{-1}.

Fig 12c, the plots related to the three different buildings are very similar in shape and in values. This means that the building geometry has little or no influence on the cooling energy demand. For the reference case (B2, SA:V = 0.25 m^{-1}), the cooling energy demand may increase by more than 70% from the optimal WWR to the worst WWR, with a non-linear trend as the WWR increases.

The energy for lighting E_L as a function of WWR is plotted in Fig. 12d, for a south exposed façade. The energy demand for lighting shows also a low dependence on the building geometry.

This is mainly due to the fact that, in the simulated buildings, a higher SA:V (i.e. building B3), corresponds with a higher ratio between the office rooms (that can exploit daylight) and other spaces (where no daylight exploitation occurs). The lowest energy consumption for lighting is achieved with high WWR, even if each WWR adopts a different shading activation set-point. E_L can be increased by more than 40%, if the worst configuration is chosen. It is worth mentioning that in Fig. 12 only data concerning south- and north-exposed façade modules are reported; however, similar conclusions and trends can be seen for the other two orientations (east-west).

4.4.2. Reliability with respect to the HVAC system efficiency

In Fig. 13, E_{tot} for HVAC systems with different efficiencies is plotted as a function of the WWR. The curves are shifted because of the higher/lower efficiency of the HVAC system, but a change in the $SCOP_{heating}$ determines very little consequences on the shape of the E_{tot} curves. The only orientation that is slightly affected by a better/worse $SCOP_{heating}$ is the north (Fig. 13b). However, since the shapes of the curves do not change (or change very little), the optimal WWR is always reached in the same interval. It is thus possible to state that the optimal configurations are independent from the efficiency of the heating systems – assuming that the $SCOP_{heating}$ stands in the range 2.6% ± 25%.

An improvement/worsening of the performance of the cooling system has a wider impact on the shapes of the E_{tot} (WWR) function instead. Higher efficiency flattens the E_{tot} curve, allowing the optimal configuration to be more transparent. For a south-exposed façade module (cf. Fig. 13a), the optimal configuration changes: from a WWR in the range 35–45% to WWR in the range of 45–55%. This behavior can be observed for all the other orientations as well (Fig. 13c and d), with very similar trend. A less efficient cooling

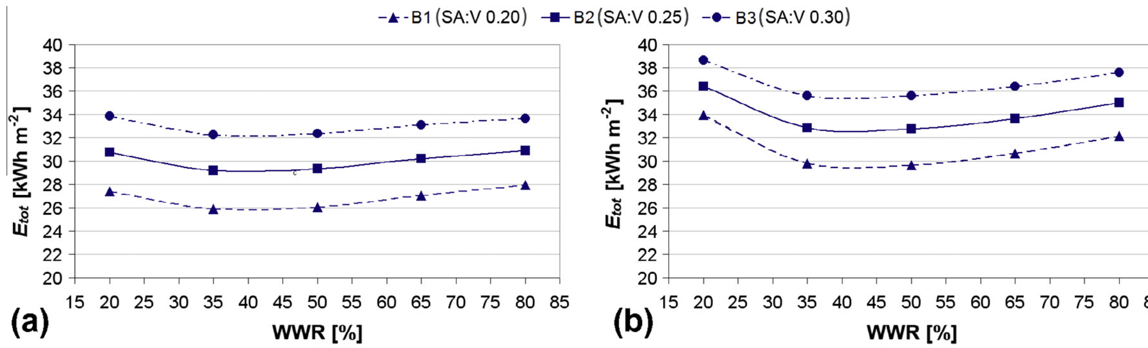

Fig. 10. Total energy demand *Etot* for different building geometries B1, B2, B3: (a) south-oriented façade module and (b) north-oriented façade module.

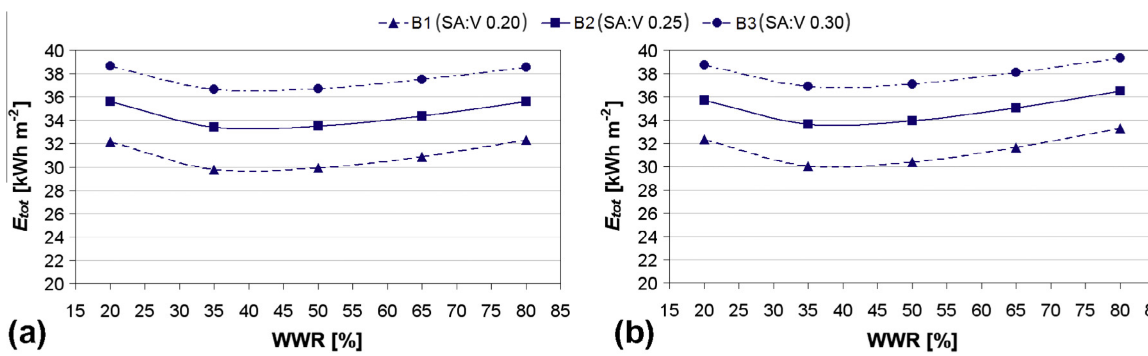

Fig. 11. Total energy demand *Etot* for different building geometries B1, B2, B3: (a) west-oriented façade module and (b) east-oriented façade module.

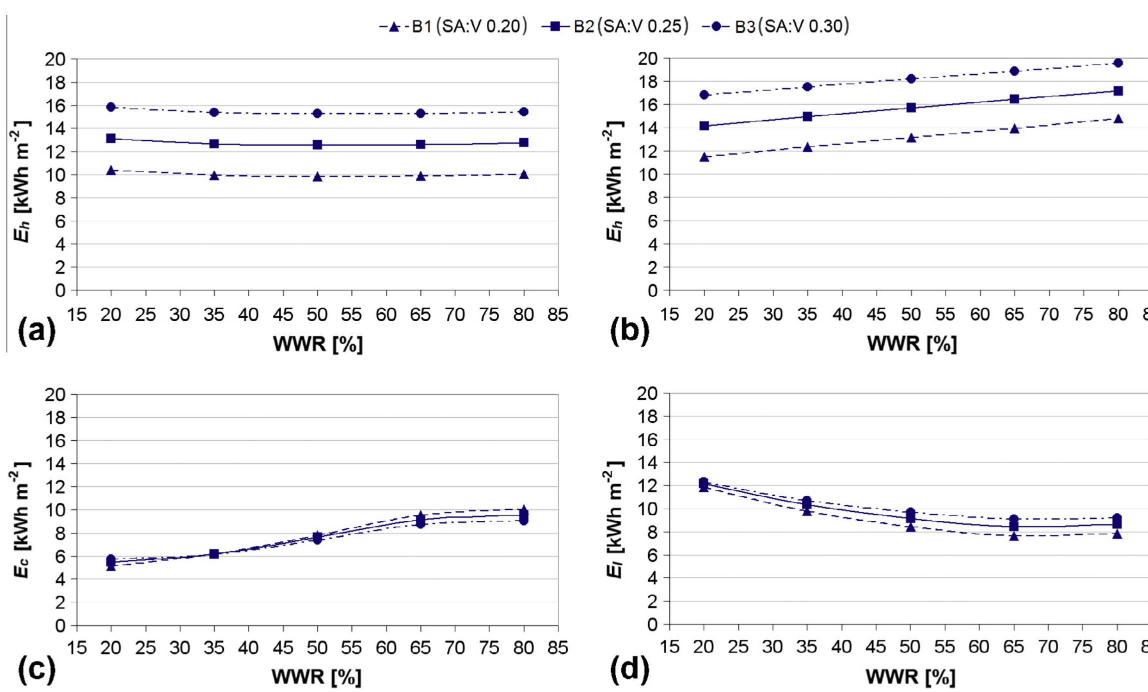

Fig. 12. (a) Heating energy demand E_H for different building geometries B1, B2, B3 (south-oriented façade module); (b) Heating energy demand E_H for different building geometries B1, B2, B3 (north-oriented façade module); (c) Cooling energy demand E_C for different building geometries B1, B2, B3 (south-oriented façade module) and (d) Lighting energy demand E_L for different building geometries B1, B2, B3 (south-oriented façade module).

system affects the shape of the E_{tot} curve too, but with a lower impact on the position of the minimum value of the E_{tot}: the optimal configuration is almost always a little less transparent (about 5% less) than the one calculated with the reference HVAC system. The south-exposed façade module (cf. Fig. 13a) is the one that is most affected by the worsening of the cooling equipment performance.

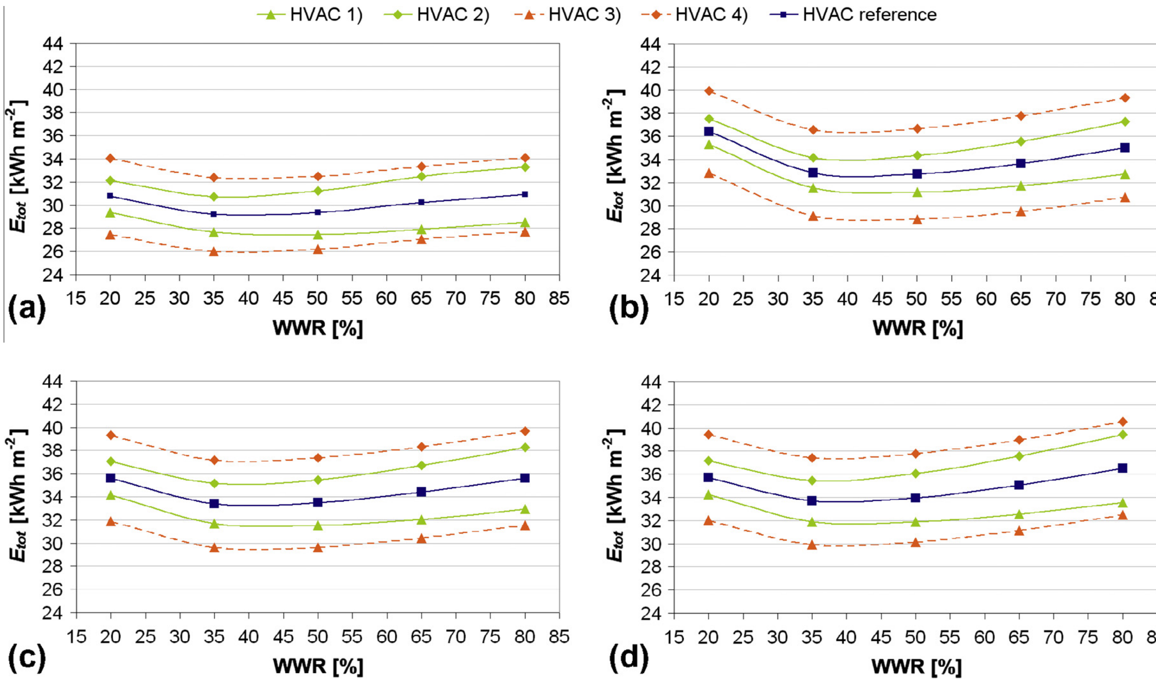

Fig. 13. E_{tot} as a function of WWR in case of HVAC systems with different efficiencies: (a) south-oriented façade module; (b) north-oriented façade module; (c) west-oriented façade module and (d) east-oriented façade module. B2, SA:V = 0.25 m^{-1}.

5. Discussions

Apparently, the search for the optimal WWR of a façade module in a low-energy office building reveals that this parameter has little influence on the final total energy demand (E_{tot}) of the building. This result is in trend with the findings from the literature review, revealing that the less the energy consumption, the less the impact of the façade on it: from a reduction up to 50% in the late Seventies [4] (when the conductance of an opaque wall was more than 5 W m^{-2} K^{-1}, single glazing was a standard solution and luminous efficacy was about 20 lm W^{-1}), down to about 16% [19] for a low energy building, and further down to about 10% in this paper.

The optimal WWR can be found, almost regardless the orientation, in the range 35% < WWR < 45%. The north orientation is that where a "wrong" WWR has the deepest impact. In this case, an increase of a little more than 11% in the E_{tot} can occur, if a low transparent percentage is chosen (WWR = 20%) instead of an optimal WWR. For the other orientations, the increase in the E_{tot} with respect to the optimal solution is between 6% and 9%. It is important to state that there seems not to be an orientation where the optimal WWR is completely different. This is a positive aspect that may allow a simplification to be done, during the first stage of the design of a building, as well as an advantage in terms of prefabrication of the façade modules.

However, it is important to underline that the technologies that are adopted by the façade are robust and efficient in term of prevention of heat losses and heat gains; furthermore, a preliminary optimization of the set-up value for activation of solar shading systems was carried out. Therefore, the chosen technology and the adopted control strategies are already optimized.

Moreover, the high density of internal loads may also play a role in the reduction of the influence of the façade on the energy demand of the building. In order to highlight this aspect, some simulations with different internal loads and presence of solar shading system are carried out and the impacts of these changes evaluated. In Fig. 14 the reference configurations (full internal loads) and the configurations without internal loads (from electric equipment and people) are shown, for a south and a north-exposed façade (Fig. 14a and b, respectively). It is possible to notice that, without internal loads, the increase in energy demand due to the worst WWR configuration is more that 20% furthermore, the optimal WWR changes too. As far as a north-exposed façade is concerned, E_{tot} increases by about 13%, and the optimal WWR changes too

As far as the use of solar shading system is concerned (Fig. 15), only south-exposed façade has been analyzed. A non-optimal WWR in case of absence of solar shading results in an increase in the in the E_{tot} of more than 50% (Fig. 15a). In case of absence of internal loads and solar shading systems (Fig. 15b), the difference on the energy demand between the best and worst WWR is only about 19%, due to the balance between the increased solar gain and the reduced internal loads. The optimal WWR under these circumstance is very similar to that of the reference configuration (full internal loads, venetian blinds).

It is therefore possible to state that the façade configuration (WWR) presents a low impact on the final energy demand, in office buildings, only if the façade is made with up-to-date technologies and managed in a proper way. The relatively low influence of the WWR on the E_{tot} is confirmed by the sensitivity analysis: the optimal WWR, within the same building type (single corridor office building with cell offices), seem to be almost independent from the exact geometry of the building, as well as from a different efficiency of the HVAC system (within a ±25% range). Only a noticeable increase in the efficiency of the cooling equipment may determine a slightly change in the optimal configurations – allowing more transparent façade modules to be realized and a decrease of the total energy demand achieved.

These findings may allow building with rather different appearances to be designed, since WWR may not determine a huge increase in the total primary energy demand of the building. On the other side, it can be highlighted that it is possible to reach an optimal configuration, which may reduce to the minimum extent – as far as allowed by the technology – the total primary energy demand of the building.

Finally, as far as the impact of different WWR on the visual environment is concerned, it can be seen that the different activation

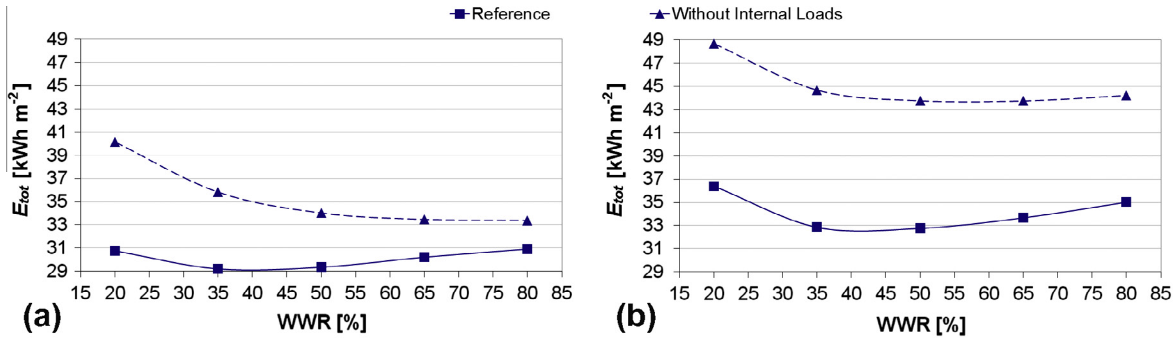

Fig. 14. Total energy demand E_{tot} for different WWR, with and without internal loads (people and equipment): (a) south-oriented façade module and (b) north-oriented façade module. B2, SA:V = 0.25 m^{-1}.

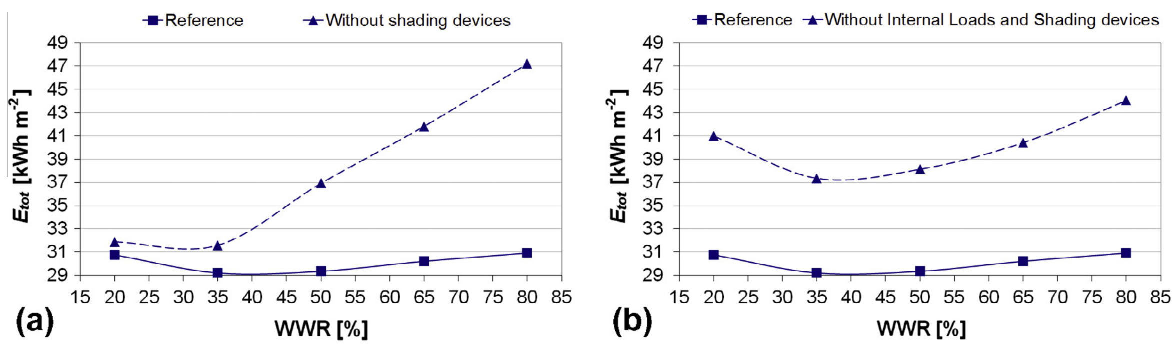

Fig. 15. Total energy demand E_{tot} for different WWR in a south-oriented façade module: (a) with and without solar shading systems and (b) without solar shading systems and without internal loads (people and equipment). B2, SA:V = 0.25 m^{-1}.

flux for each WWR (and orientation) reduces the influence of the different WWR. The daylighing conditions are very similar for all WWR, except for the lowest values (20% < WWR < 30%): under these circumstances, the DA is lower than 50% for some orientations and $UDI_{500–2000}$ is lower than 45% for all the orientation. No substantial differences are revealed as far as the orientations are concerned only in a north-oriented façade (where venetian blinds are never displaced) $UDI_{500–2000}$ reaches higher value compared to other façade orientations, especially for high WWR ($UDI_{500–2000}$ = 70% in case of WWR = 65%). South, west and east-exposed façades also show very similar trends of $UDI_{>2000}$. It is important to remember that a dedicated research activity [27] has shown the tendency of *Energy Plus* to overestimate the illuminance level, though this inaccuracy is still acceptable. As result of this fact, simulations of the visual environment may present a lower degree of accuracy, compared to thermal simulations.

6. Conclusion and future work

The results of the research activity show that the configuration (WWR) of an advanced façade module (with state-of-the-art technologies) has a low influence on the total primary energy demand of the building. The north-exposed façade is the one that may suffer the most when a wrong configuration is adopted, while the south-exposed façade is the one where the influence of WWR is the lowest. The minimum total primary energy demand is always achieved when WWR is in the range of 35–45%. In this range, daylighting conditions are also satisfactory and this WWR can therefore be considered a good starting point in preliminary design phase. The analyses show little dependence of E_{tot}(WWR) on the building geometry and the HVAC efficiency. A far higher dependency is revealed if the internal loads are changed, or if the solar shading systems are not (properly) activated. This behavior can be explained by considering that the influence of the façade in the case of a low-energy building is much lower than it used to be in conventional building – provided that state-of-the-art technologies are adopted, and that solar shading systems (and their activation) are optimally exploited.

The method has been applied in this paper to an office building located in a temperate oceanic climate, that represents a large area of Atlantic and Central Europe, and results are therefore significant for this climate only. In the future, the method can be applied to different locations in order to highlight the influence of each climate on the optimal WWR and to give advices for façade design of low-energy office buildings in different climates.

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